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**ELECTRICAL CHARACTERIZATION
OF ELECTROPHORETICALLY COATED ALUMINUM SAMPLES
FOR PHOTOVOLTAIC CONCENTRATOR APPLICATION**

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ABSTRACT

The practicality of using a thin-film styrene/acrylate copolymer electrophoretic coating to isolate concentrator cells electrically from their surroundings in a photovoltaic concentrator module is assessed. Only the electrical isolation problem was investigated. The approach was to subject various types of EP-coated aluminum specimens to electrical stress testing and to aging tests while monitoring coating electrical resistivity properties. It was determined that, in general, longer processing times--i.e., thicker electrophoretic layers--resulted in better voltage-withstand properties. In particular, a two-minute processing time seemed sufficient to provide the electrical isolation required in photovoltaic concentrator application applications. Even though electrophoretic coatings did not seem to fill voids in porous-anodized aluminum substrates, breakdown voltages generally exceeded hi-pot pass-fail voltage levels with a comfortable margin.

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SECTION 1

INTRODUCTION

1.1 OBJECTIVE

The objective of this investigation was to assess the capability of electrophoretic coatings to provide an adequate level of voltage standoff when used in photovoltaic concentrator modules. The focus was on the reliability and durability of Sandia-provided samples consisting of an electrophoretically applied thin-film - a styrene/acrylate copolymer - on aluminum substrate material.

1.2 BACKGROUND

Photovoltaic concentrator module technology involves using Fresnel lenses or other means to focus light onto a relatively small area of silicon. Concentrator technology thus requires much less silicon (the most expensive part of photovoltaics) to capture a given amount of sunlight or to produce a given amount of electricity. However, since concentrated light is used, some means for removing excess heat from the silicon solar cells must be included in the module designs.

The need to remove heat must be balanced by the requirement that the solar cell string must be electrically isolated from any exterior conducting surfaces (such as metal housing or heat sinks). Over the years, a number of approaches have been used, such as ceramic (alumina) substrates or thin layers of dielectric sheet, but most of these approaches have had problems with thermal conductivity, voltage-standoff capabilities, cost, or any combination thereof. Electrophoretic coatings show promise of solving these problems by providing a low-cost, conformal coating with high-voltage electrical standoff capabilities that can be made thin enough and/or combined with anodization layer to provide good heat transfer from the solar cells to heat rejection components.

Field experience with concentrator modules has identified a number of failures due to unacceptable leakage-current levels and has highlighted the growing recognition for advanced materials that specifically address the concerns of adequate dielectric strength coupled with good thermal conductivity. An important requirement for achieving safe, high-reliability concentrator modules is to utilize cost-effective materials capable of achieving safe levels of dielectric withstand between the cell circuitry and the external environment. At the same time the materials must provide good heat transfer so that photovoltaic cell operating temperatures are not too high.

Electrical isolation of typical first-generation concentrator modules was achieved by using ceramic wafers (i.e., alumina, Al_2O_3) to isolate the solar cell from external components.

Aluminum heat sinks were used to remove heat. This type of construction uses costly materials, and is complicated by the number of assembly steps. An approach that shows promise is to apply a conformal coating to the aluminum housing that provides the necessary dielectric strength and still is thin enough to ensure adequate thermal transfer between the cell and the housing or heat sink.

Historically, module safety and voltage withstand reliability have been assured by passing a "hi-pot" test [1]; the pass/fail criterion of this test is that a voltage equal to twice maximum, open-circuit system voltage plus 1000 V_{DC} impressed for one minute between cell circuitry and housing will result in a leakage current below 50 microamps. Typical concentrator system voltages are anticipated to be on the order of 600 V_{DC}, requiring a dielectric withstand capability on the order of 2200 V_{DC}.

1.3 ELECTROPHORESIS

Electrophoresis is the migration of an electrically charged species under the driving influence of an electric field. Coating technologists associate the term with the electrodeposition of a mixture of charged organic species from an aqueous electrolyte solution. Dispersants, surfactants and emulsifiers are added to the electrolyte to form a colloid. After electrodeposition, the sample is cured to drive off water and cross-link the polymer, resulting in a conformal coating of uniform thickness. Although the principles of electrophoresis are similar to those of electrodeposition of metals, application by industry was delayed until paints and lacquers were developed that contained binders which form ionized particles when diluted with an aqueous solution [2].

The advantages to concentrators of using electrophoretically deposited dielectrics are: (1) coating uniformity over the entire surface including seams, corners, edges, cavities and concealed surfaces; (2) controllability of coating thickness; (3) low porosity and superior adhesion; and (4) increased corrosion resistance. Disadvantages include: (1) high initial costs; (2) stringent facility requirements (space and cleanliness); (3) stringent process control (bath temperature, voltage); and (4) greater sensitivity towards pretreatment [3].

Recent efforts at Sandia have resulted in a number of refinements to an electrophoretic process for coating aluminum alloy substrates with a DuPont Corp. resin, Eldep^R, a styrene/acrylate copolymer, in use for a number of years in the automotive industry as a corrosion-resistant coating for large steel substrates such as automobile parts [4].

1.4 TEST SAMPLE DESCRIPTION

Table 1 describes the four sets of samples that were provided to JPL by Sandia for characterization over the course of this investigation. The samples generally consisted of sheet aluminum of various alloys, sizes and electrophoretically coated/anodized configura-

ations. The first set consisted of three sizes of samples that included 1-in. squares, 2-in. squares, and 4-in. squares, and was provided for exploratory testing. The samples were 6063T-6 aluminum-alloy substrate material upon which styrene/acrylate copolymer was electrophoretically deposited.

The second set consisted of six 4-in. squares of porous-anodized (approximately 1-mil), 6061 aluminum-alloy substrate material upon which styrene/acrylate copolymer was electrophoretically deposited. Anodization, as a surface preparation, was an attempt to benefit from the known electrical isolation properties of the Al_2O_3 coating that resulted.

The third set consisted of ten 2" x 3" samples of hard anodized (approximately 1-mil) 5005 H-34 aluminum substrate material upon which styrene/acrylate copolymer (approximately 15 microns) was electrophoretically deposited.

The fourth set consisted of twelve, large area, 9" x 12" samples of hard anodized (approximately 1-mil) 3003 and 5005 aluminum substrate material upon which styrene/acrylate copolymer (approximately 20 microns) was electrophoretically deposited using a "double-dip" process involving two passes through the styrene/acrylate copolymer bath.

1.5 REPORT ORGANIZATION

Section 2 of the report provides test details. Section 3 provides test results. Section 4 provides a summary, guidelines for improving reliability, and recommendations for improved concentrator designs.

Table 1. Description of Samples.

SAMPLE SET	SIZE(S)	SUBSTRATE	ANODIZATION	THICKNESS OF ELECTROPHORETIC LAYER
1	1" x 1" 2" x 2" 4" x 4"	Al-alloy 6063-T6	None	~ 15 μ m
2	4" x 4"	Al-alloy 6061	Porous ~1-mil	1 μ m - 10 μ m, varies with number of defects
3	2" x 3"	Al-alloy 5005 H-3	Hard ~1-mil	~ 15 μ m
4	4" x 4"	Al-alloy 3003	Hard ~1-mil	~ 20 μ m Double-dipped
	4" x 4"	Al-alloy 5005	Hard ~1-mil	~ 20 μ m Double-dipped

SECTION 2

TEST PLAN

The investigation began with exploratory testing of the first set of samples to confirm voltage breakdown measurements made at Sandia National Laboratories. After verifying the relative breakdown-strength measurements, bulk ionic conductivity measurements of the styrene/acrylate copolymer layer were made. Subsequent measurements of the remaining sets of samples were made to electrically characterize the resistance of the styrene/acrylate copolymer to high-voltage stresses. A Biddle Instruments partial discharge detection system was used to determine the corona inception and dielectric breakdown voltage levels.

2.1 MEASUREMENTS USING A PARTIAL DISCHARGE DETECTION SYSTEM

To characterize resistance to electrical breakdown, samples of the styrene/acrylate copolymer material were subjected to high-voltage stresses using a Biddle Instruments partial discharge detection apparatus, Figure 1, to measure: (1) corona inception voltage; (2) a 100-second pulse-energy spectrum of the insulation (pulse height analysis); and (3) the dielectric voltage breakdown level.

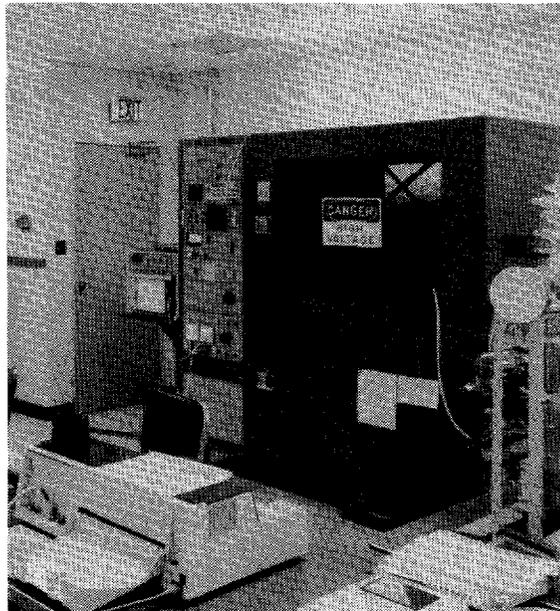


Figure 1. Biddle High-Voltage Partial Discharge Detection System.

The negative lead of the high-voltage supply was connected directly to the aluminum substrate material, made accessible by grinding the styrene/acrylate copolymer and surface preparation (i.e., anodization), and the positive lead of the high-voltage supply was connected to a 1-in. dia., flat-surfaced, brass electrode in direct contact with the styrene/acrylate copolymer. The positive electrode had 1/16" rounded edges to minimize voltage stress concentrations. A 1-in. dia. was selected over smaller diameters (1/16" dia., 1/8" dia. and 1/4" dia.) so as to stress more flaws per test since preliminary test results suggested that flaws (voids) within the styrene/acrylate copolymer would be a significant factor in determining the maximum corona inception and dielectric voltage breakdown levels. Figure 2 shows details of the test setup within the Biddle chamber.

2.1.1 CORONA INCEPTION VOLTAGE MEASUREMENTS

Discharges occurring within cracks or voids in insulation materials are generally referred to as "corona." When an electric field passes through a gas and solid in series, the gas will break down at an applied voltage level much less than that required to break down the solid. A transfer of electrons and ions occurs across the gas resulting in a redistribution of charge on the walls of the gas pocket. The redistributed surface charge pattern gives rise to a field that opposes the applied field and the process is arrested almost instantaneously, extinguishing the discharge. In the case of direct voltage, subsequent discharges do not occur until previously deposited surface charges are dissipated through leakage, a function of temperature and relative humidity [5].

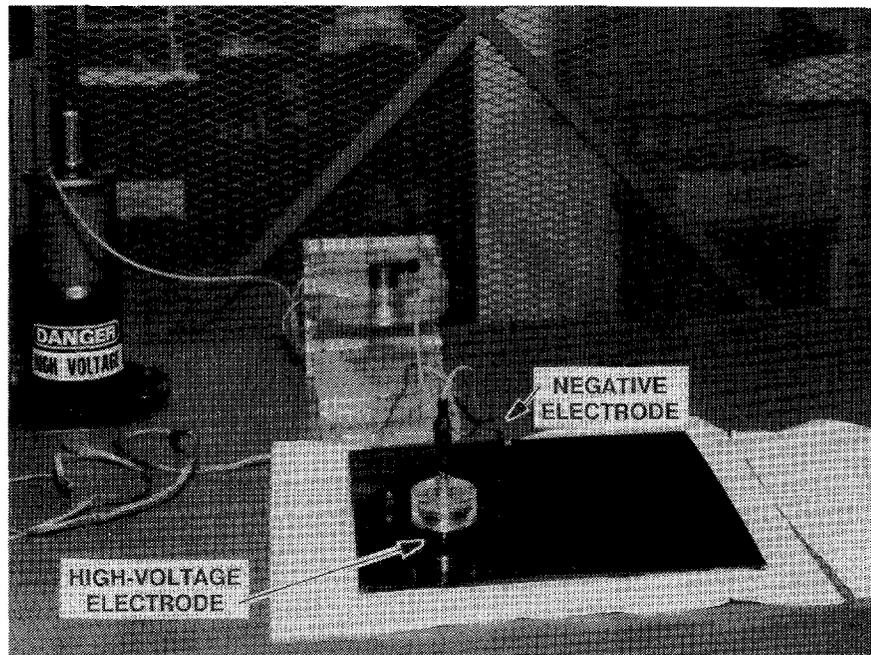


Figure 2. Identification and Attachment of High-Voltage and Negative Electrodes to the Sample Within the Biddle chamber.

Each individual discharge is a pulse of current lasting less than 0.1 microsecond. The magnitude of the detectable charge transfer generally varies from less than 1 picocoulomb (10^{-12} coulombs) to several thousand picocoulombs. The amount of energy in each pulse is on the order of 10^{-7} to 10^{-9} watt-seconds, of which only a small percentage is delivered to the insulator surface, the majority being dissipated in the gas via collision mechanisms [5].

Corona inception voltage (CIV) is the voltage at which the average magnitude of detected pulses within voids of the styrene/acrylate copolymer material exceeds a specified level [6]. For this investigation the CIV was arbitrarily chosen to be that voltage at which a 5 pC discharge level was achieved and sustained. Although these measurements can be made without any disturbance to the samples, the voltage was usually raised beyond the corona inception voltage to achieve breakdown, i.e. a penetration through the dielectric layer.

Since the point of the investigation was to explore the electrical characteristics of the electrophoretic coating material and not to establish absolute voltage breakdown levels, an attempt was made to maintain the voltage at or near the corona inception voltage level when conducting a pulse height analysis. In most of the tests the corona inception voltage level was maintained long enough to obtain a 100-second pulse-energy spectrum, although in a number of cases the actual breakdown level was reached before the end of the pulse height analysis.

2.1.2 PULSE HEIGHT ANALYSIS

The 100-second pulse-energy spectrum of the insulation (pulse height analysis) is useful in determining the average power dissipated during discharges within voids. The pulse-energy spectrum is important because each discharge results in a small amount of damage to the void walls; continual discharges form trees within the insulation that ultimately develop into breakdown channels. For the electrophoretic material used in this study, styrene/acrylate copolymer deposited over an anodized aluminum substrate, data was obtained either at an impressed voltage equal to the corona inception voltage or at 5000 V_{DC} , whichever was lower.

2.1.3 DIELECTRIC BREAKDOWN

The principal measure of dielectric strength is the voltage level that results in breakdown, V_{BD} . For many of the samples tested during the course of this investigation, the breakdown voltage was found to be slightly greater than, but close to the corona inception voltage.

2.2 BULK IONIC CONDUCTIVITY MEASUREMENTS

Bulk ionic conductivity measurements were performed at room temperature and humidity (approximately 23°C/50% RH) on 4" x 4" samples to obtain an indication of how good the electrophoretic coating is as an insulator. Figure 3 is a diagram of the test setup and the spring-loaded probe assembly, and a schematic of the test circuit. Test measurements were made inside the Biddle chamber to minimize the influence of EMI, and a guard-ring electrode was used to eliminate the effects of surface conductivity. Voltage V_s was supplied to a positive lead connected to the corner of the sample. The negative lead was connected to a spring-loaded, cylindrical probe assembly consisting of the negative lead and a concentric guard-ring electrode that was placed on the surface of the sample. R_{EP} is the electrophoretic coating resistance and I is the electrical current.

The cylindrical probe assembly, Figure 3, consists of an insulating rod with electrical contact achieved through a circular disc of Chomerics^R RFI gasket material, approximately 1/8" thick, that is impregnated with silver spheres to complete the electrical circuit. The guard electrode consists of a ring of the same material concentric to the circular disc that is connected to the negative lead of the power supply. A spring maintains contact between the cylindrical probe assembly and the styrene/acrylate copolymer surface to complete the measuring circuit.

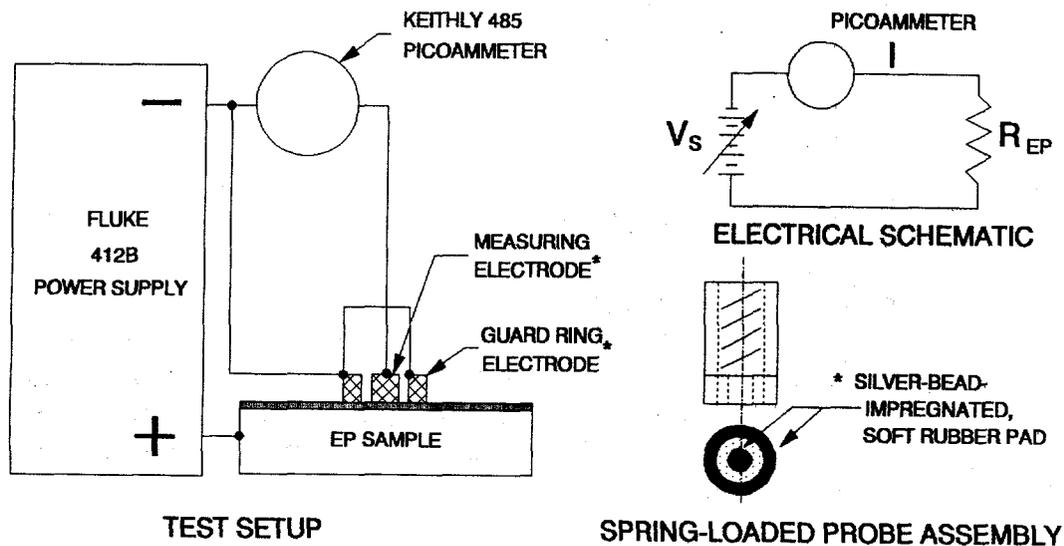


Figure 3. Diagram of the Test Setup for Bulk Ionic Conductivity Measurements.

Bulk ionic conductivity, k , is the reciprocal of the resistivity, ρ , that was calculated from the information in Figure 3 and the following equations, where r is the radius of the probe and t is the thickness of the styrene/acrylate copolymer:

$$R_{EP} = \frac{V_s}{I}$$

$$\rho = \frac{\pi r^2}{t} (R_{EP}) \quad \rho \equiv \text{resistivity}$$

$$= \frac{\pi r^2}{t} \left(\frac{V_s}{I} \right) \quad r = 0.3 \text{ cm}$$

$$t = 0.0025 \text{ cm}$$

$$\rho = 113.1 \left(\frac{V_s}{I} \right) \quad (\Omega\text{-cm})$$

The bulk ionic conductivity, k , is:

$$k = \left[113.1 \left(\frac{V_s}{I} \right) \right]^{-1} \quad (\Omega - \text{cm})^{-1}$$

2.3 ENVIRONMENTAL EXPOSURE TESTS

Two samples were subjected to a constant chamber environment of 85°C/85% RH and 1-sun UV exposure for a period of 750 hours. The samples were mounted so that one surface received 1-sun direct UV. The samples were removed from the chamber to perform bulk ionic conductivity measurements. Changes in bulk ionic conductivity over time were monitored as an indicator of the effects of accelerated environmental stresses provided by the chamber environment.

Additional environmental tests involving in situ monitoring of the changes in bulk ionic conductivity with the sample in a chamber environment of 85°C/85% RH and 1-sun UV exposure met with very limited success attributed to the high relative humidity within the chamber that enabled numerous leakage paths to ground, making measurements highly suspect.

SECTION 3

EXPERIMENTAL TEST RESULTS

The data to be presented summarizes the results of testing of the four sets of samples described in Section 1.4, Table 1. Subsection titles in this Section correspond to each to each of the four sample sets: electrophoretically deposited, high-temperature styrene/acrylate copolymer on 6063T-6 aluminum alloy aluminum substrates; varying thicknesses of the same high-temperature styrene/acrylate copolymer but applied over porous anodized (approximately 1.5-mil Al_2O_3), 6061-T6 aluminum substrates; 15 microns of the styrene/acrylate copolymer applied over approximately 1-mil hard anodized 5005 H-34 aluminum substrates; and 20 microns of styrene/acrylate copolymer, using a double-dip process, over hard-anodized type 3003 and 5005 aluminum substrates.

3.1 ELECTROPHORETICALLY DEPOSITED, HIGH-TEMPERATURE STYRENE/ACRYLATE COPOLYMER ON 6063T-6 ALUMINUM-ALLOY SUBSTRATES

3.1.1 Exploratory Bulk Ionic Resistivity and Environmental Exposure Tests

Prior to inserting the samples in an environmental test chamber, exploratory bulk ionic resistivity measurements were obtained at 23°C/50% RH using improved instrumentation with a low background noise level, Figure 3. These measurements indicated a resistivity on the order of 10^{16} ohm-cm, a very high value. This is nearly three orders of magnitude better than EVA and 6 orders of magnitude better than PVB. These test results indicate that the styrene/acrylate copolymer coating is a very good electrical insulator.

After approximately 100 hours at 85°C/85% RH and 1-sun UV exposure, bulk ionic resistivity measurements were still on the same order of magnitude as measured at the start of the test (10^{16} ohm-cm). After approximately 400 hours of exposure, the samples, viewed while still in the chamber, showed no visible signs of degradation. However, after 750 hours of exposure, the samples showed discoloration and their resistivity had dropped by two orders of magnitude (10^{16} ohm-cm to 10^{14} ohm-cm). Although this level of degradation is significant, it may be acceptable for some photovoltaic concentrator applications. The UV testing was terminated at this point, although additional testing may be warranted when the use environment is better defined (an electrophoretically coated area under the lens is not usually exposed to direct UV, while coating the entire housing presents a different combination of environmental stresses).

3.1.2 Exploratory Characterization of Resistance to Electrical Breakdown

The purpose of the exploratory characterization tests were to corroborate results between the Sandia tests and the JPL Biddle tests, and to provide a check of the Biddle performance. Table 2 identifies the samples and provides a comparison of the Sandia and JPL test results. Exploratory characterization of resistance to electrical breakdown was conducted on three samples (4" x 4") that were subjected to high-voltage, direct current stresses from the Biddle partial discharge equipment to detect corona inception voltage levels (sensitivity was set at 5 pC charge). Maximum test voltage ranges were either 5 kV_{DC} or 10 kV_{DC}. The samples were not exposed to UV at JPL prior to these tests.

The two samples were selected on the basis of Sandia voltage breakdown test results with Sample #1 indicating relatively inconsistent processing, as evidenced by its poor electrical performance -- breakdown voltage levels occurred between 0.55 kV_{DC} and 1.70 kV_{DC}; and Samples #3 and #5 indicating relatively good processing, as evidenced by their excellent performance -- breakdown voltage levels occurred at 2.5 kV_{DC} or greater. Performance results from Samples #3 and #5 indicate that the electrophoretic coating is relatively free of flaws and of sufficient thickness to provide good electrical insulation resistance. Note that in comparing the test results from Sandia with those of JPL, the Sandia test voltage was limited to a maximum of 2.50 kV_{DC}.

For the Samples #1 and #3, tested at JPL, the corona inception voltage levels occurred very near their voltage breakdown levels of 2.8 kV_{DC} and 6.9 kV_{DC}. In the case of Sample #1, the consensus is that variations in the thickness of the electrophoretic coating may have accounted for the JPL test result of 2.8 kV_{DC} compared to the highest test result, 1.7 kV_{DC}, obtained by Sandia. For concentrator applications whose system voltage is no more than 600 V_{DC}, the data from these two tests suggest that the electrophoretic coating material is a candidate capable of passing the high-voltage breakdown test of 2200 V_{DC} (2 x V_{SYSTEM} + 1000 V_{DC}).

Table 2. Corroboration between Sandia and JPL Test Results.

SAMPLE SET 1	V _{BD} (kV _{DC}) SNL Results			V _{BD} (kV _{DC}) JPL Results		
	#1 (Back)	1.55	0.55	1.70	2.80	
#3 (Back)	2.50*	2.50*	2.50*	6.90		
#5 (Front)	2.50*	2.50*	2.50*	3.25***	3.00***	3.25***
* Sandia tested to 2.50 kV _{DC} maximum, breakdown did not occur.						
*** Corona inception voltages (kV _{DC})						

3.2 ELECTROPHORETICALLY DEPOSITED, HIGH-TEMPERATURE STYRENE/ACRYLATE COPOLYMER ON POROUS-ANODIZED 6061 ALUMINUM-ALLOY SUBSTRATES

Although an anodic layer is considered to be a good electrical insulator, the anodization process introduces material flaws that make the anodic layer by itself a relatively poor electrical insulator. Sandia has indicated that the electrophoretic application of styrene/acrylate copolymer is intended to fill any voids, thus producing a flaw-free dielectric layer consisting of the anodization layer plus the styrene/acrylate copolymer layer.

The second set of samples employed an anodization layer in addition to the EP coating. This set of six (6) samples underwent six different electrophoretic bath processing times ranging from "dip and dry" to 4 minutes, and was tested at Sandia for electrical breakdown susceptibility. Table 3 provides a description of the samples and a listing of Sandia test results. Each sample was tested at six different locations, three on the front surface and three on the back surface. The results indicate relatively consistent processing results with the longer processing time providing a higher degree of voltage breakdown strength.

Table 4 summarizes the JPL test data for Samples #1, #2, #3 and #4, indicating the corona inception (or breakdown) voltage, average current, and the average power dissipated in a 100 second pulse height analysis at the corona inception voltage. The trend of the test data compares favorably with results obtained by Sandia. In general, JPL results indicate that a sample processing time of two minutes is adequate to provide a level of dielectric strength more than sufficient for concentrators whose system voltage is on the order of 750 volts. The poor test result for one location on Sample #3 (voltage breakdown at 1.75 kV) is believed to be due to a defect, since the rest of the test results by Sandia and JPL were generally indicative of good processing.

The test data for Sample #4, processed for 4 minutes, exhibit corona inception at approximately 3000 Vdc. Corona inception levels for this sample set are lower than for Sample Set 1, although one sample (Table 2) whose corona inception level was 3.25 KV_{DC}, was tested successfully to 10 KV_{DC} without experiencing a breakdown.

Due to the small sample size (4" x 4"), it was difficult to obtain a statistically significant number of data points. Sample-to-sample variation was rather significant and the consensus was that the electrophoretic coating did not successfully fill in all of the defects of the porous anodized coating as intended.

Results from the Biddle partial discharge detection equipment are shown in Table 4 and are in good agreement with Sandia results confirming that the longer processing times (i.e., thicker electrophoretic layers) result in better voltage withstand capability.

Table 3. Sandia Voltage Breakdown Test Results.

SAMPLE SET 2	DESCRIPTION		TEST #					
			1	2	3	4	5	6
#1	SO4 EP6	30 Sec	850	1050	950	1010	950	1050
#2	SO4 EP10	60 Sec	2050	2500	1650	2500	2350	1650
#3	SO4 EP12	120 Sec	2500	2500	2500	2500	2500	4500
#4	SO4 EP5	240 Sec	5000	5000	5000	5000	5000	5000
#5	SO4 EP11	Dip/dry	900	950	1075	925	975	1000
#6	SO4 EP7	Control	1450	1350	1500	1425	1300	1650

Table 4. JPL Partial Discharge Detection Test Results.

SAMPLE SET 2	SAMPLE ID	CIV (kV)	V _{BD} (kV)	Average Current Dissipated (pA)	Average Power Dissipated (nW)
#1	#1F F0 65 2	--	0.95	--	--
#1	#1F E5 45 2	--	0.90	--	--
#1	#1F F5 35 2	--	0.80	--	--
#2	#2F B5 65 2	1.05	--	35	173
#2	#2F E0 55 2	1.05	--	54	269
#3	#3F D5 45 2	--	1.75	--	--
#3	#3F F5 65 2	1.85	--	75	374
#4	#4F B5 65 2	3.45	--	--	--
#4	#4F F0 60 2	3.12	--	123	383
#4	#4F C0 30 2	3.15	--	102	323
#4	#4F F0 25 2	3.3	--	103	340

Note: -- indicates data not taken.

3.3 ELECTROPHORETICALLY DEPOSITED, HIGH-TEMPERATURE STYRENE/ACRYLATE COPOLYMER ON HARD-ANODIZED 5005 H-34 ALUMINUM-ALLOY SUBSTRATES

Measurements were obtained for ten 2" x 3" samples consisting of approximately 1-mil hard anodized 5005 H-34 aluminum electrophoretically coated with approximately 15 microns of styrene/acrylate copolymer. Although there was quite a bit of data scatter, all measured corona inception voltages were above the intended field operating voltage of 750 V_{DC}. As the data in Table 5 show, measured CIV's vary from under 1 kV_{DC} to over 3 kV_{DC}. In almost all cases where breakdown occurred, the measured breakdown voltage was at or very near the corona inception level.

For high quality (flaw free) samples, the corona inception voltages are higher than field operating voltages, and in many cases exceed the voltage level used by industry as a measure of satisfactory long-term field performance. For concentrator systems whose system voltage is no more than 750 V, these high-quality samples would pass the Sandia high-voltage breakdown (hi-pot) test (twice system voltage + 1000 V_{DC}), [1].

Table 5. Test Results Indicating Corona Inception Voltage (CIV) and Voltage Breakdown (V_{BD}) Levels for Ten Samples: Hard Anodized 5005 H-34 Aluminum Electrophoretically Coated with Styrene/Acrylate.

SAMPLE SET 3	SAMPLE ID	CIV (kV _{DC})	V _{BD} (kV _{DC})	Average Current Dissipated (pA)	Average Power Dissipated (nW)
#Z06	Z06F 40 B5	3.71	--	119	442
#Z07	Z07F 40 B5	1.67	--	11	18
#Z08	Z08F 40 B5	1.12	3.35	985	1100
#Z09	Z09F 40 B5	2.00	--	100	199
#Z10	Z10F 40 B5	2.47	2.47	881000	2180000
#Z11	Z11F 40 B5	3.70	--	141	523
#Z12	Z12F 40 B5	0.85	2.74	564	479
#Z13	Z13F 40 B5	3.54	--	51	179
#Z14	Z14F 40 B5	2.77	--	141000	3900000
#Z15	Z15F 40 B5	2.82	--	160	451
Note: -- indicates data not taken.					

Although above the 2.2 KV_{DC} required for concentrator systems, Figure 4 is representative of voltage breakdown showing a number of breakdown sites caused by a sustained 2.77 KV_{DC}. Figure 5 is the corresponding 100-second pulse-energy spectrum (Sample Z14F 40 B5) of the insulation, indicating an average power dissipation in void discharges of 3,900 microwatts (Compare this with the pulse height analysis of a sample using an improved "double dip" electrophoretic process, Figure 8).

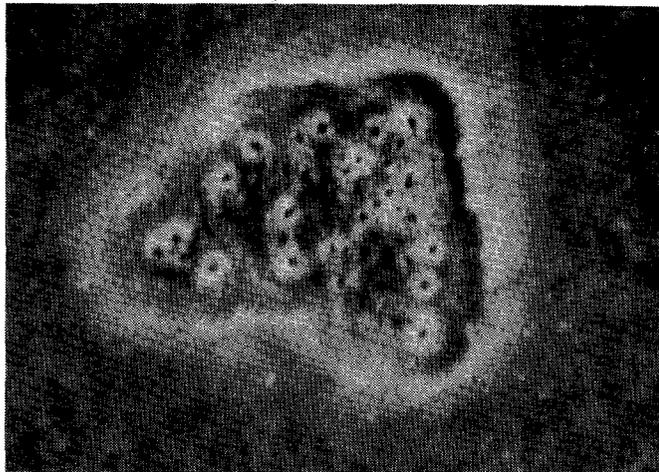


Figure 4. Representative Example of Voltage Breakdown Site Showing Numerous Breakdowns (70X magnification).

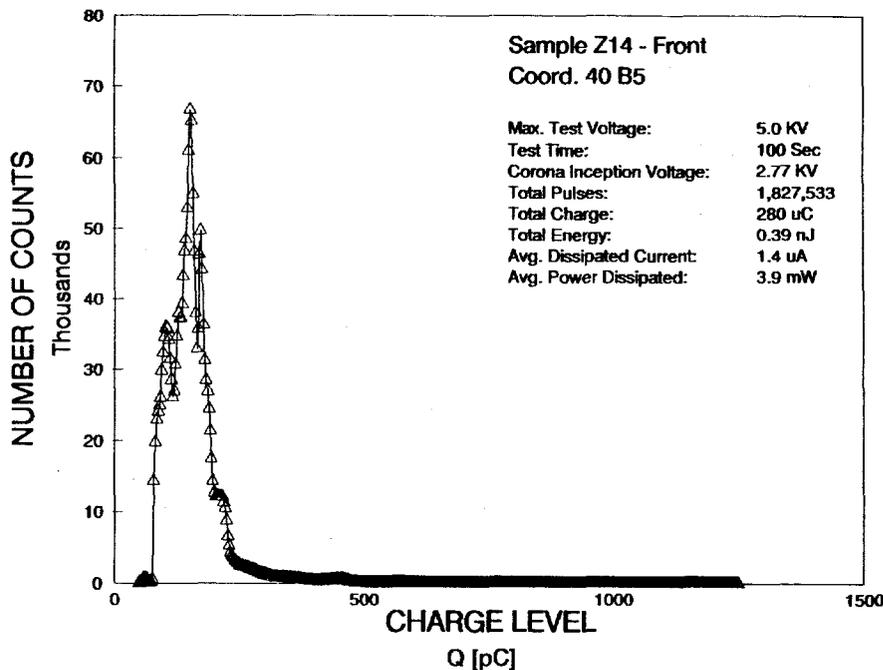


Figure 5. Pulse Energy Spectrum (2" x 3" Sample) Indicating the Number of Counts as a Function of Charge Level, Q [pC].

3.4 ELECTROPHORETICALLY DEPOSITED, HIGH-TEMPERATURE STYRENE/ACRYLATE COPOLYMER ON HARD-ANODIZED 3003 and 5005 ALUMINUM-ALLOY SUBSTRATES

Measurements of twelve, large area (~9" x ~12") EP samples were also completed. The partial discharge detection apparatus was limited to a maximum applied voltage of 5 kV_{DC} and the circuit used a 1-in. dia. flat-surfaced brass electrode with 1/16" rounded edges. The samples consist of approximately 1-mil hard anodized aluminum (six samples of 3003 aluminum and six samples of 5005 aluminum) electrophoretically coated with approximately 20 microns styrene/acrylate copolymer, shown in Figure 6.

These samples have included the latest Sandia-developed process refinements consisting of an improved "double dip" method that involves a second pass through the styrene/acrylate copolymer bath in conjunction with a higher voltage to expose "weak" spots (flawed regions) and then "recoating" them at this higher voltage. This technique is intended to minimize or eliminate flaws that result in high electrical stress concentrations.

Between 24 and 30 sites per sample were tested for dielectric withstand (high-voltage breakdown) measurements. Figure 7 is a typical data sheet used to record the following data for each site: corona inception voltage, and breakdown voltage identified by an asterisk (*) or the 5 KV_{DC} limit followed by the number of picocoulombs of charge transfer.

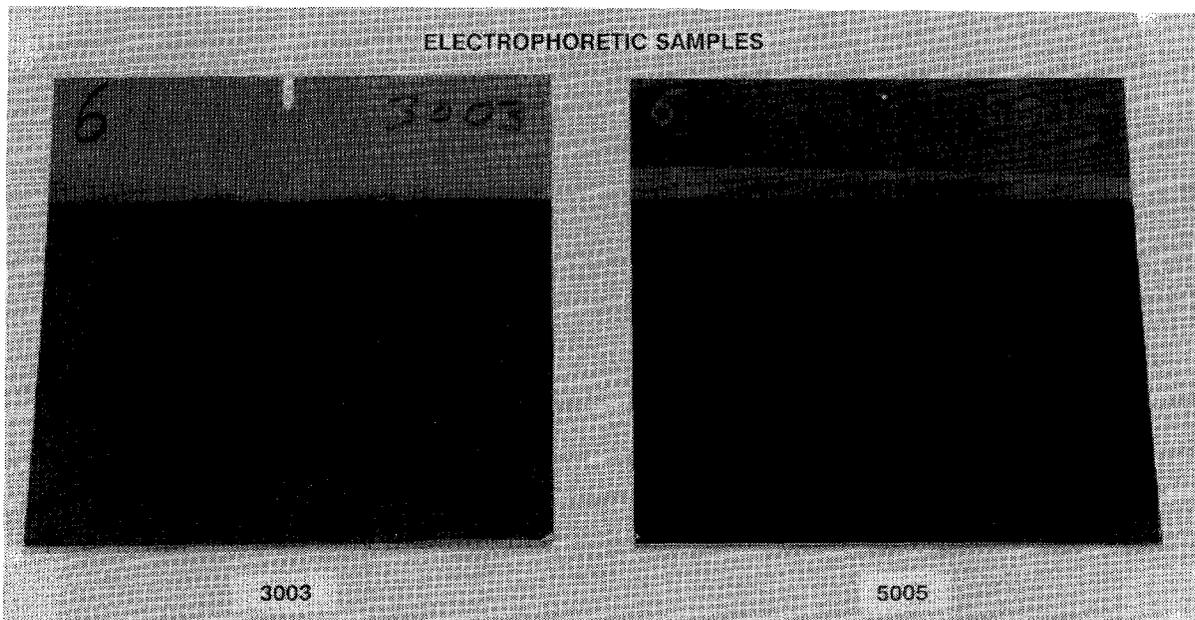


Figure 6. 12" x 12" Samples of 3003 and 5005 Hard Anodized (~1- mil) Aluminum Electrophoretically Coated (~20 microns) Styrene/Acrylate Copolymer.

SAMPLE: 1 - FRONT		TYPE: 3003 Al		DATE: 05/09/90		INIT: RSS/GRM						
A	3.4 KV 4.3 KV *	2.9 KV 5.0 KV *	3.2 KV 5.0 KV 22 pC	3.2 KV 5.0 KV 24 pC	2.9 KV 5.0 KV 26 pC	3.2 KV 5.0 KV 24 pC						
B												
C	3.3 KV 5.0 KV 15 pC	3.2 KV 5.0 KV 18 pC	3.5 KV 5.0 KV 19 pC	3.4 KV 3.7 KV *	3.2 KV 5.0 KV 30 pC	2.6 KV 4.7 KV *						
D				3.8 KV 5.0 KV 11 pC								
E	3.3 KV 5.0 KV 28 pC	3.1 KV 5.0 KV 23 pC	3.4 KV 5.0 KV 13 pC	3.2 KV 5.0 KV 19 pC	3.2 KV 5.0 KV 20 pC	2.9 KV 5.0 KV 25 pC						
F												
G	3.3 KV 5.0 KV 24 pC	3.3 KV 5.0 KV 13 pC	3.2 KV 5.0 KV 14 pC	3.3 KV 5.0 KV 17 pC	3.3 KV 5.0 KV 23 pC	2.6 KV 5.0 KV 31 pC						
H												
I	3.1 KV 4.3 KV *	3.4 KV 5.0 KV 20 pC	3.6 KV 4.0 KV *	3.8 KV 5.0 KV 12 pC	3.1 KV 5.0 KV *	2.9 KV 5.0 KV 22 pC						
	1	2	3	4	5	6	7	8	9	10	11	12

Figure 7. Typical Data Sheet for Corona Inception Voltage and Voltage Breakdown Levels Up to a Maximum of 5 KV.

Figure 8 is a pulse energy spectrum for an electrophoretic sample indicating the Number of Counts as a Function of Charge Level, Q [pC]. This is a typical result for the pulse height analysis data of a 3003 aluminum substrate (Sample 3003-1) taken at a single point using the Biddle Instruments partial discharge detection apparatus. The 100-second pulse-energy spectrum measurement was used to determine the average power dissipated in the voids of the electrophoretic coating. Note the difference in magnitude of the average power dissipated: 1.57 microwatts for Sample 3003-1 versus 3,900 microwatts for Sample Z14F 40 B5 (Figure 5), whose electrical insulation has completely failed. Note that although the shape of the two curves is essentially the same, the ordinate for Sample Z14 40 B5 is an order of magnitude greater and the abscissa is three orders of magnitude greater than for Sample 3003-1.

For the six samples of 3003 aluminum, corona inception voltage ranged from 1.5 KV_{DC} to 3.8 KV_{DC}, significantly higher than the envisioned concentrator system voltage level, 600 V_{DC}. The lowest measured voltage breakdown level occurred at 2.6 KV_{DC}, well above the dielectric voltage breakdown level determined to be acceptable by Sandia ($V_{BD} = 2.2$ KV_{DC}). Figure 9 shows the cumulative probability distribution as a function of voltage breakdown level for each of the six samples.

For the six samples of 5005 aluminum, the lowest measured voltage breakdown level occurred well below 1 KV_{DC}. Figure 10 shows the cumulative probability distribution as a function of voltage breakdown level for each of the six samples. Note that only one sample had all sites in excess of the qualification test hi-pot voltage level of 2.2 KV_{DC}.

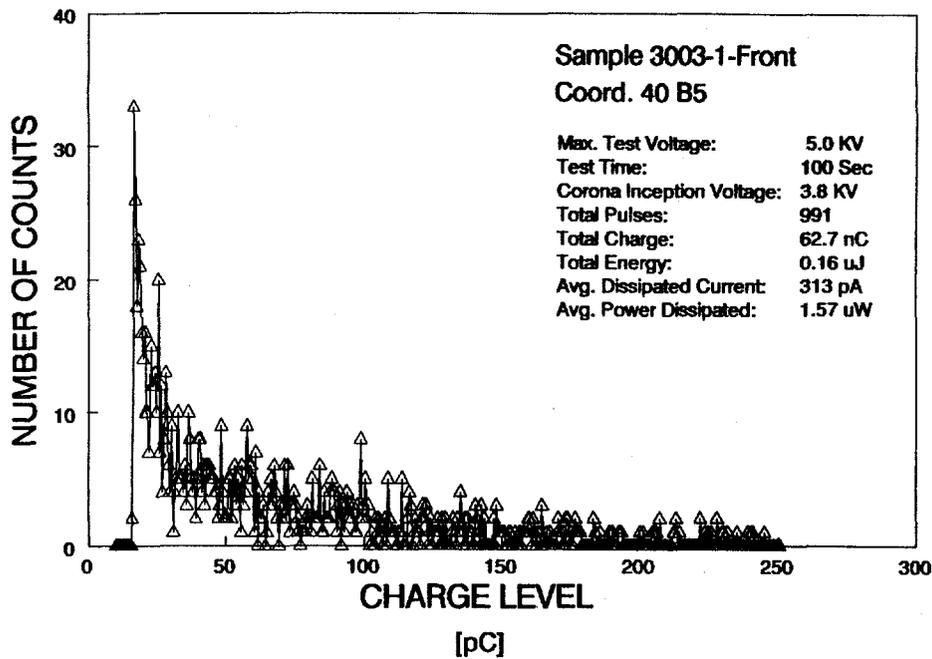


Figure 8. Pulse Energy Spectrum (9" x 12" Large-Area Sample) Indicating the Number of Counts as a Function of Charge Level, Q [pC].

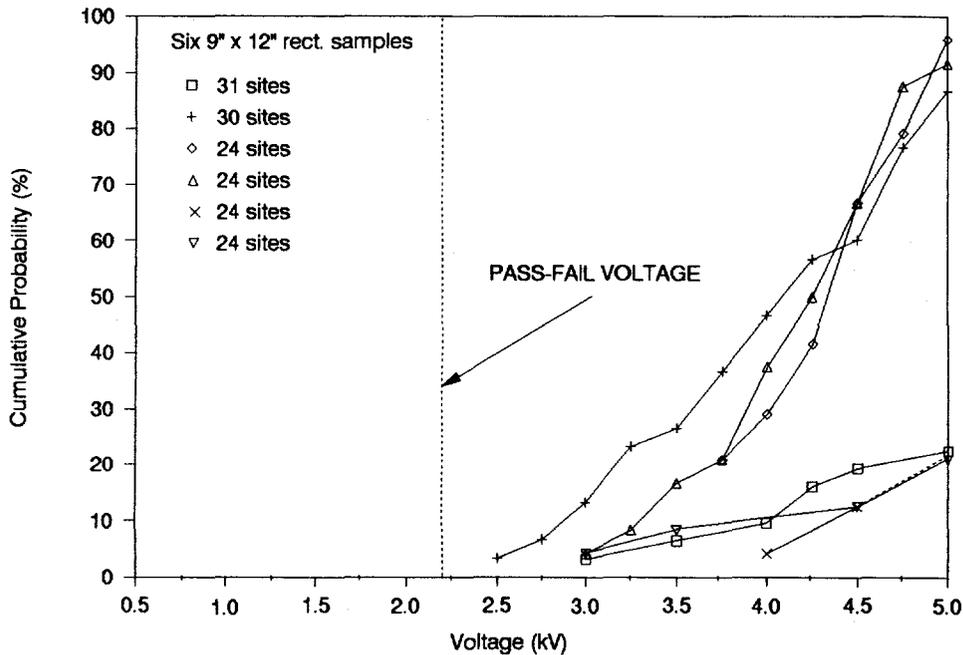


Figure 9. Cumulative Voltage Breakdown Probability Distribution for Six Individual Samples of Hard Anodized 3003 Aluminum Alloy with Styrene/Acrylate Copolymer.

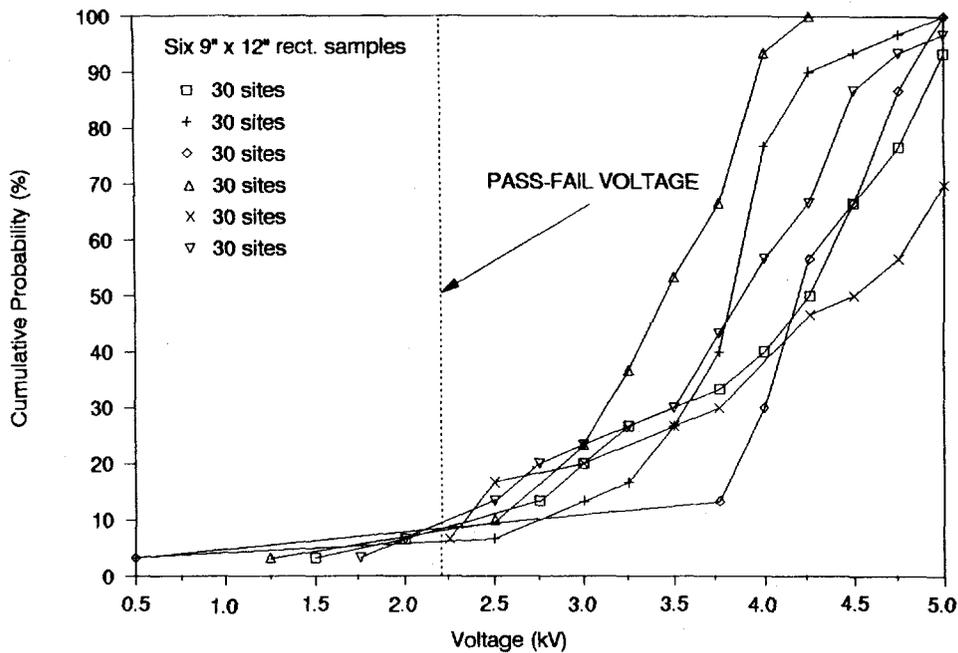


Figure 10. Cumulative Voltage Breakdown Probability Distribution for Six Individual Samples of Hard Anodized 5005 Aluminum Alloy with Styrene/Acrylate Copolymer.

Figure 11 shows the cumulative probability distribution as a function of voltage breakdown level for all sites associated with each type of aluminum. As indicated there is an approximately 6% probability that the 5005 aluminum will have a voltage breakdown below the 2.2 KV_{DC} level. Voltage breakdown levels for the 3003 aluminum exceeded the voltage level used by the industry as a measure of satisfactory long-term field performance, indicative of high quality (flaw-free) samples.

The test results show that for concentrator systems whose system voltage is no more than 600 V, these high quality 3003 aluminum samples would pass the Sandia 2.2 KV_{DC} breakdown test requirement.

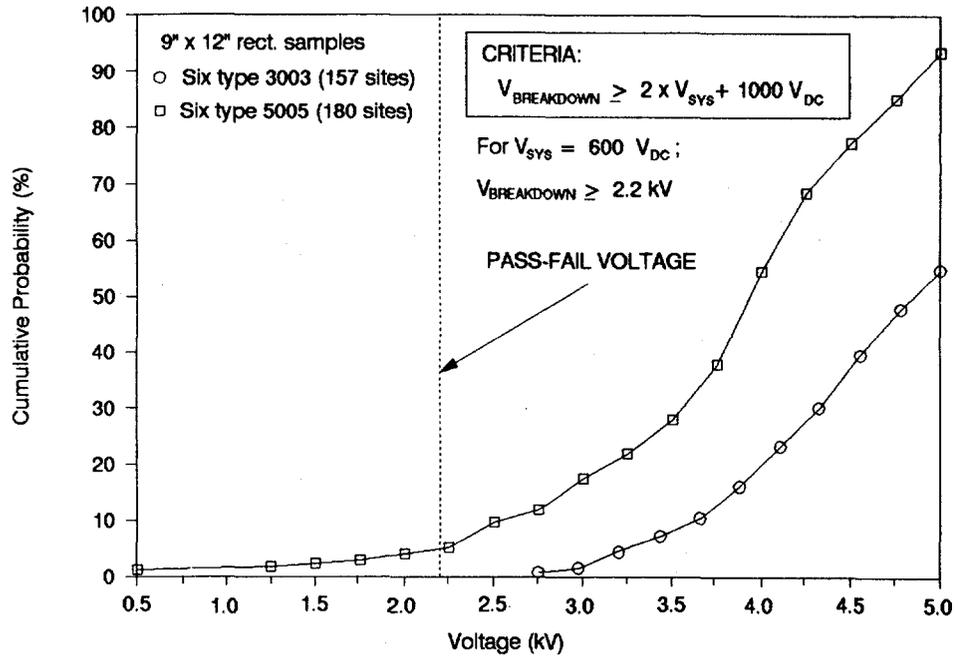


Figure 11. Cumulative Voltage Breakdown Probability Distribution for Hard Anodized 3003 and 5005 Aluminum Alloy with Styrene/Acrylate Copolymer.

SECTION 4

SUMMARY

4.1 EVALUATION

Achieving acceptable levels of dielectric strength requires avoiding or minimizing the generation of corona discharges that eventually lead to insulation breakdown. Dielectric materials should have uniform density and be free of voids, air gaps and impurities. They should have low ionic conductivities and bond well to the aluminum substrate.

A candidate process has been developed at Sandia that electrophoretically deposits a 20-um layer of styrene/acrylate copolymer onto a hard anodized, 3003 aluminum plate. Results from characterization tests of these samples at JPL indicate that the material has sufficient dielectric strength to withstand up to 2200 V_{DC}; a level that should provide an adequate level of personnel safety for photovoltaic concentrator systems operating at up to 600 V_{DC}.

4.2. CONCLUDING REMARKS

Results of testing large numbers of samples indicate that dielectric strength at a specific site is flaw dependent, indicating that voltage breakdown levels for an electrophoretic coating is highly process dependent. Flaw origination is believed to result from several sources including: (1) material preparation - cleaning and quality of anodization layer; (2) purity of bath - more difficult to achieve for the larger area/volume requirements associated with concentrator housings; (3) voids within the electrophoretic layer - a function of bath temperature, voltage/current/time variables, and curing. A major factor determining the success of this technology is the ability to repeat the process to obtain a high-quality coating. Additional testing may be warranted to verify adequate control of the process variables.

Regarding voltage breakdown, currently accepted practice is to rely on "hi-pot" test results: leakage current not to exceed 50 uA for one minute application of twice maximum system voltage plus 1000 V_{DC}. Results of testing to date indicate that the corona inception voltage level may also be a valuable indicator of the potential for failure. Since continual discharges form trees within the insulation that ultimately develop into breakdown channels, a good material selection criterion is that the corona inception voltage should be well above the system operating voltage. Review of corona inception voltage data indicates that for most of the tested sample sites corona inception voltage levels are well above the anticipated system operating voltage.

Finally, JPL recommends conducting experiments to verify that dielectric withstand and corona inception voltage levels are still adequate after long periods of exposure to typical outdoor stresses including temperature, relative humidity, UV, dust and airborne contaminants.

SECTION 5

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